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Fuzzy-adapted linear interpolation algorithm for image zooming

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ABSTRACT

This work presents a novel fuzzy linear interpolation algorithm with application in image zooming. Fuzzy logics are employed to derive suitable weights for the neighboring samples in the interpolation formulae. By considering local gradients to calculate the weights, the accuracy of the interpolated value is improved. Additionally, a modification of the proposed algorithm based on the interpolation error theorem is developed to deal with images containing ridges and valleys. Both quantitative results obtained by measuring the peak signal-to-noise ratio (PSNR) and perceptual observations assessed the superior performance of the proposed algorithm and its modified version with respect to the state-of-the-art interpolation methods.

1. Introduction

Essential to many image processing procedures, image interpolation is widely adopted to reproduce a high-resolution (HR) image from a low-resolution (LR) version in many applications. Interpolation turns available discrete images into spatially continuous images that are crucial for geometric transformation of digital images. Numerous interpolation approaches have been developed in earlier years [1,2]. Several well-known and commonly used methods, such as the bilinear, bicubic, and cubic spline interpolation schemes, calculate the interpolated value as a weighted sum of the neighboring samples. However, these conventional interpolation approaches do not consider local features and thus may blur local structures or cause undesirable artifacts in reproduced HR images.

Recently, a large number of interpolation approaches have been proposed to improve perceptual quality of reproduced images by considering edge features. In [3], an edge-preserving interpolation scheme is proposed; this scheme uses a nonlinear filter that can accurately reconstruct sharp edges. A simple $2\times$ interpolator that operates within a 3×3 mask is presented in [4]; this interpolator is equivalent to pixel replication followed by nonlinear correction. In [5], a linear framework based on the evaluation of a warped distance between an interpolated pixel and its neighbors is presented. This warped distance then replaces the Euclidean distance in conventional interpolation formulae. Li and Orchard propose an edge-directed interpolation algorithm that is adapted to edge orientation using the local covariance measurements of LR images [6]. Furthermore, a hybrid framework that combines bilinear interpolation and covariance-adapted interpolation is developed to reduce computational complexity. Two adaptive interpolation approaches that use inverse gradients to conventional schemes are presented in [7]. Zhang and Wu introduce an edge-guided interpolation algorithm based on linear minimum mean-square-error estimation and propose a simplified version that significantly reduced the computational effort [8]. Yoo derives a closed-form formulation for adaptive linear image interpolation based on least-squares techniques [9]. Moreover, there are various interpolation approaches that

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perform well in reproducing HR images [10–19]. Wang and Ward propose an orientation-adaptive method that reduces zigzagging effects in edges and ridges by adopting the isophotes in images [10]. Several nonlinear interpolation methods attempt to enlarge an image by intelligent schemes, such as neural networks [20,21], optimal recovery [22], and vector quantization [23]. Another extensively researched subfield of image interpolation is implemented in wavelet domain [24–26]. The vital disadvantage of wavelet-based approaches is that the non-integer magnification factor cannot be used. Among most interpolation methods, the quality of obtained HR images strongly depends on the interpolated accuracy, particularly in locally detailed regions. Accordingly, an effective framework that considers locally detailed features is essential to obtain HR images of high quality.

To improve the quality of the interpolated images, we present a smart linear interpolation scheme that adapts the interpolation weights according to a set of fuzzy rules. The presented fuzzy rule based system (FRBS) is utilized to obtain a new distance that replaces the Euclidean distance in interpolation formulae. A modified scheme based on the interpolation error theorem is then introduced to deal with specified features, in particular, ridges and valleys. Experimental results verify the superiority of the proposed algorithms working on image zooming and related applications.

The rest of this paper is organized as follows. Section 2 briefly introduces the conventional linear interpolation method and then describes the motive underlying this work. Section 3 presents the main configuration of the proposed interpolation algorithms. Section 4 first demonstrates two one-dimensional (1-D) models for parameter determination and execution time measurements. Experimental results presented in numerical comparisons and visual illustrations are then compared with those processed by other interpolation methods. A conclusion is briefly made in Section 5.

2. Preliminaries

2.1. Review of linear interpolation

Linear interpolation, a curve-fitting technique using linear polynomials, is widely employed in numerical analysis and various applications, such as that for enhancing image resolution. For simplicity, Fig. 1 presents a simple one-dimensional example to explain conventional linear interpolation scheme. Let $f(x_i)$ be the discrete sample at sampling node x_i of an ideal signal $f(x)$ that is unknown. Without loss of generality, assume the spacing between adjacent sampling nodes is one, i.e., $x_{i+1} - x_i = 1$. For any interested point $x \in [x_i, x_{i+1}]$, the value of $\hat{f}(x)$ calculated by a linear interpolation method is formulated as

$$\hat{f}(x) = (1-s)f(x_i) + sf(x_{i+1}), \tag{1}$$

where s is the distance defined as $s = x - x_i$ $(0 \leqslant s \leqslant 1)$.

Suppose a given point (x, y) exists in the squared division $[x_i, x_{i+1}] \times [y_j, y_{j+1}]$ in an image. The value of $\hat{f}(x,y)$ via a sequence of row-wise and column-wise interpolation procedure, called bilinear interpolation, is given by

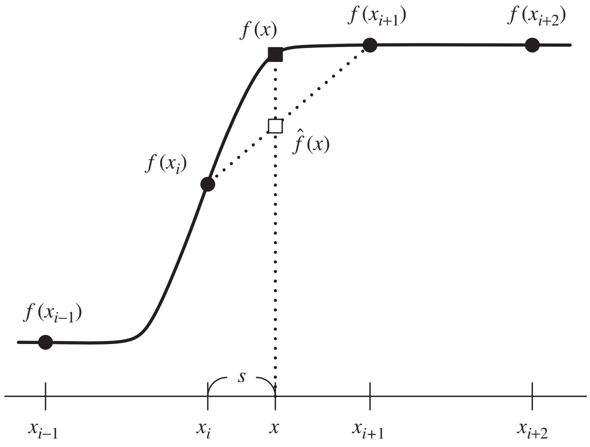

Fig. 1. One-dimensional case of conventional linear interpolation.

$$\hat{f}(x,y) = (1-t)[(1-s)f(x_i,y_j) + sf(x_{i+1},y_j)] + t[(1-s)f(x_i,y_{j+1}) + sf(x_{i+1},y_{j+1})], \tag{2}$$

where $s = x - x_i$ $(0 \leqslant s \leqslant 1)$ and $t = y - y_j$ $(0 \leqslant t \leqslant 1)$ are distances on the horizontal and vertical axes, respectively.

2.2. Problem description

The estimates calculated from (1) and (2) may not be sufficiently accurate to represent the ideal value. In particular, if the considered pixel belongs to a sharp image region where the values change abruptly, the weights of neighboring samples must be modified not only taking into account distance measurements but also spatial features. The new idea underlying this work is to produce an adapted distance to replace the original distance by additionally involving local gradients. Thus the accuracy of interpolated values from (1) and (2) is certainly improved.

Consider the simple function (Fig. 1) again. Let symbols ■ and □ represent the ideal value and the interpolated value obtained by linear interpolation, respectively. The interpolated value $\hat{f}(x)$ does not correctly represent ideal function $f(x)$ as point x locates in the sharp region $[x_i, x_{i+1}]$ where $f(x)$ changes abruptly, and there exists an interpolation error defined as $e = |\hat{f}(x) - f(x)|$. Based on human knowledge, either decreasing the weight of $f(x_i)$ or increasing the weight of $f(x_{i+1})$ effectively reduces this undesirable error. Moreover, modifying the weights in (1) and (2) can be regarded as replacing the distance s with another new distance $\hat{s}$. Consequently, the objective is to identify a workable transformation $\varphi: \Re \to \Re$ between s and $\hat{s}$ such that the interpolation error can be minimized.

3. The proposed method

Fuzzy logics are extensively adopted in numerous engineering applications; in particular, for approximating